Clumped isotope carbonate thermometry & paleoaltimetry of the Colorado Plateau

Kate Huntington (kateh@gps.caltech.edu), Brian Wernicke, John Eiler

What is the source of buoyancy for cratonic plateau uplift?

Uplift timing key to mechanism for Colorado Plateau rise

The Colorado plateau region experienced 500 My of subsidence and deposition below sea level as part of the stable North American craton. Unlike the rest of the craton, the Plateau was uplifted ~2 km since the Late Cretaceous with little internal upper crustal strain. Proposed **mechanisms** for Colorado Plateau rise are related to:

(1) Sevier-Laramide contractional deformation (80-40 Ma)
crustal thickening due to channel flow (e.g. McQuarrie & Chase, 2000), convective removal of lithospheric mantle (England & Houseman, 1988), chemical modification of lithosphere by volatile addition from Laramide flat slab (Humphreys et al., 2003)

(2) Mid-Tertiary buoyancy addition (40-30 Ma)
demise of Laramide flat slab, partial removal of plateau lithosphere & replacement with hot asthenosphere (Spencer, 1996), chemical modification through melt extraction along plateau margins (Roy et al., 2005)

(3) Late Tertiary regional extension (post 30 Ma)
heating lithosphere from below (Thompson & Zoback, 1979) possible mantle plume (Parsons & McCarthy, 1995), convective removal of the lithospheric mantle (Bird, 1979; Humphreys, 1995)

Geologic observations provide uplift timing constraints, but need absolute paleoaltimetry to account for rest of modern elevation, relate relative elevations to sea level, and quantify post-50 Ma uplift history.

Existing constraints:

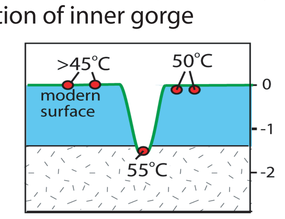
(1) Modern elevation ~2 km a.s.l.

(2) Marine strata of Grand Canyon section deposited 80 Ma

(3) Drainage reversal 20-40 Ma
(e.g., Elston & Young, 1991)

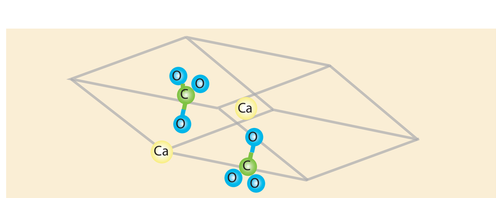
(above) Landsat image of Colorado River N of Grand Canyon. Drainage pattern indicates flow to NE, modern flow to SW.

(4) Early-Tertiary (>50 Ma) incision of kilometer-scale proto canyon at position of inner gorge



(Flowers et al., 2007; Flowers et al., in review)

Paleoelevation from clumped isotope thermometry

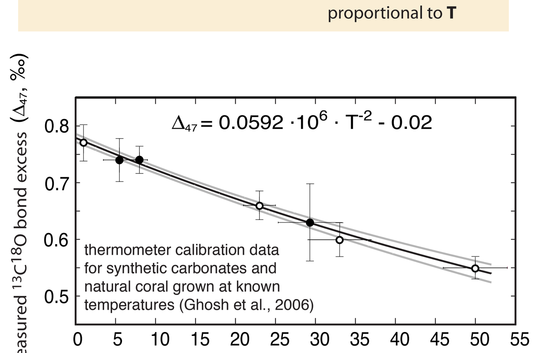


carbonate ion exchange reaction:

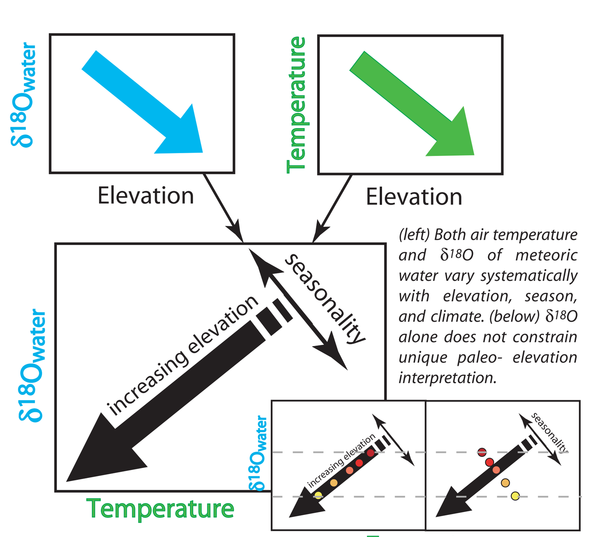
$$^{12}C^{18}O^{16}O_2 + {}^{13}C^{16}O_3 \underset{K}{\rightleftharpoons} {}^{13}C^{18}O^{16}O_2 + {}^{12}C^{16}O_3$$

equilibrium constant increases with decreasing **T**

$^{13}C^{18}O$ bond excess proportional to **T**



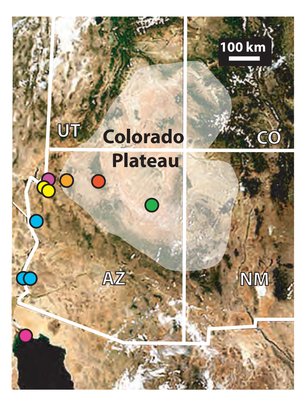
The clumped isotope thermometer independently determines carbonate growth temperature and the $\delta^{18}O$ of water from which the carbonate grew, potentially enabling the effects of elevation, climate, and seasonality to be distinguished.



(left) Both air temperature and $\delta^{18}O$ of meteoric water vary systematically with elevation, season, and climate. (below) $\delta^{18}O$ alone does not constrain unique paleo- elevation interpretation.

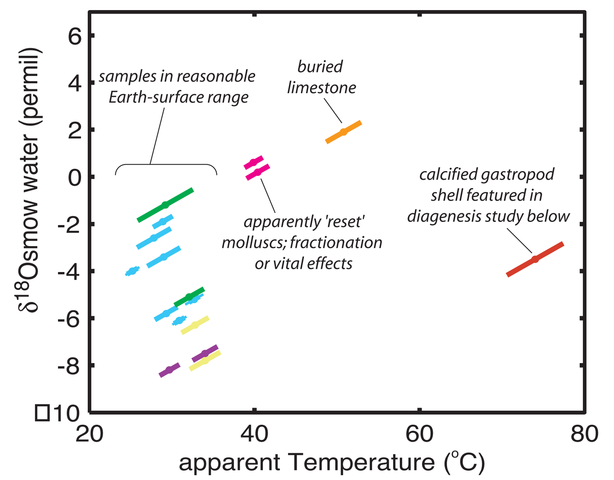
What materials potentially access paleoelevation information?

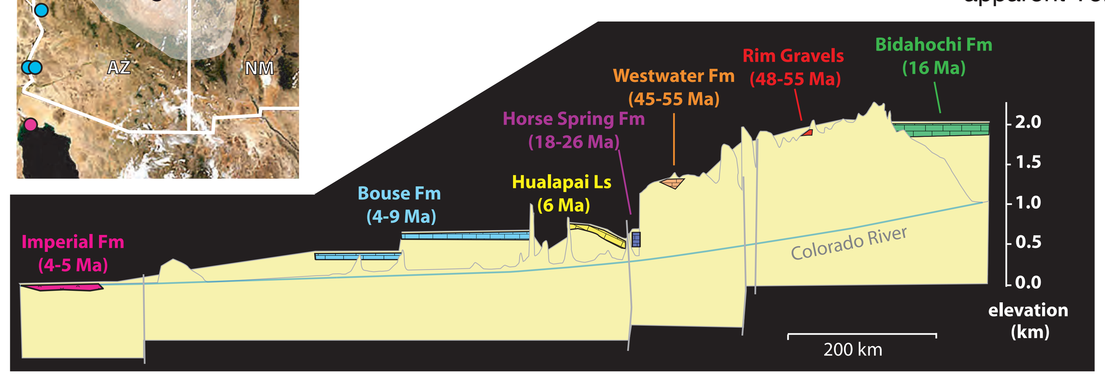
(below, right) Diverse carbonates including gastropods, molluscs, barnacles, soil, marl, tufa, and limestone from Cretaceous to Pliocene deposits from and adjacent to the Plateau record temperatures between 24-75°C and d18OSMOW water values of 2 to -8 permil.



LEGEND
- Rim Gravels, ~55-24 Ma (calcified gastropod)
- Westwater Fm, 55-45 Ma (limestone)
- Rainbow Gardens H.S., ~18-26 Ma (micrite, soil)
- Bidahochi Fm, 16 Ma (marl)
- Bouse Fm, 4-9 Ma (micrite, marl, barnacles)
- Imperial Fm, 4-5 Ma (molluscs)
- Hualapai, ~6 Ma (tufa, marl)

Error bars shown represent 95% confidence interval for 2-4 replicate analyses



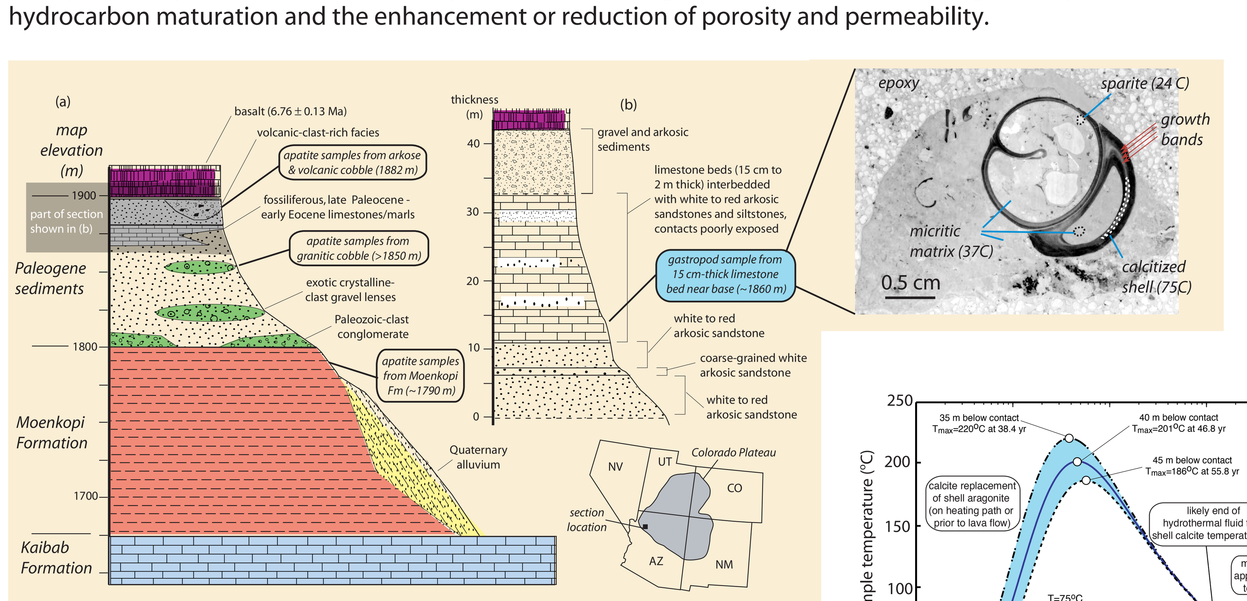


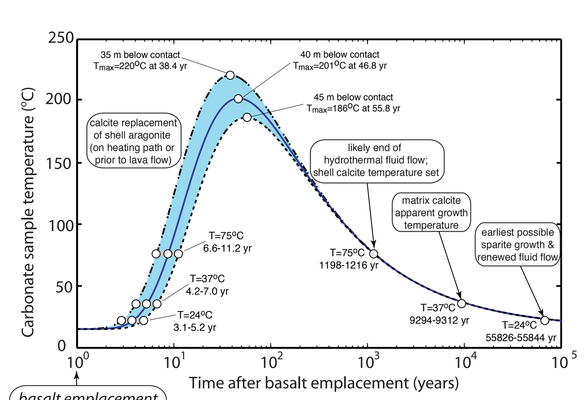
Most samples represent reasonable Earth surface conditions, but temperatures in excess of ~33°C likely record carbonate recrystallization/replacement temperatures during burial metamorphism ('resetting').

Although fossils are vulnerable to resetting, fine-grained (impermeable) micrites consistently yield temperatures within the plausible Earth-surface range, suggesting that resistance to diagenesis is grain size dependent.

Application of 'reset' samples to diagenesis & hydrocarbon studies

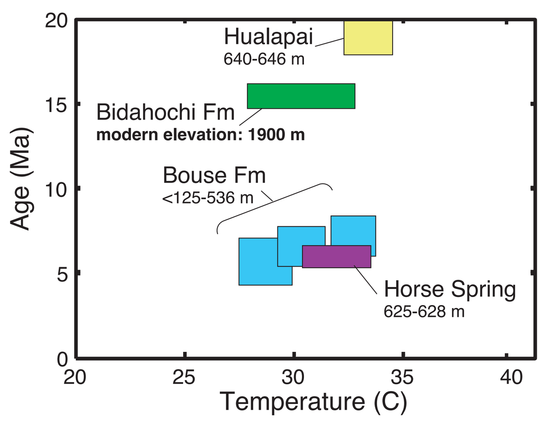
Clumped isotope thermometry shows promise for relating thermal histories and diagenetic processes that modulate hydrocarbon maturation and the enhancement or reduction of porosity and permeability.





(above) Three generations of carbonate in the same sample record calcite replacement and precipitation at temperatures of 24-75°C. (right) This record can be related to the sample's modeled thermal history following nearby basalt emplacement (6.76±0.13 Ma, Billingsley, 1996) to estimate the timing of porosity and permeability modification due to calcite growth during diagenesis.

Plateau uplift timing based on elevation dependence of lake carbonate temperatures

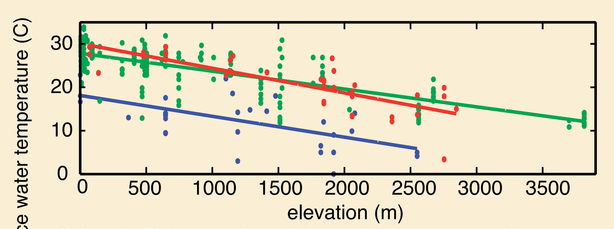


Robust estimates indicate warm temperatures for samples deposited at low elevation (modern elevations <650 m a.s.l)

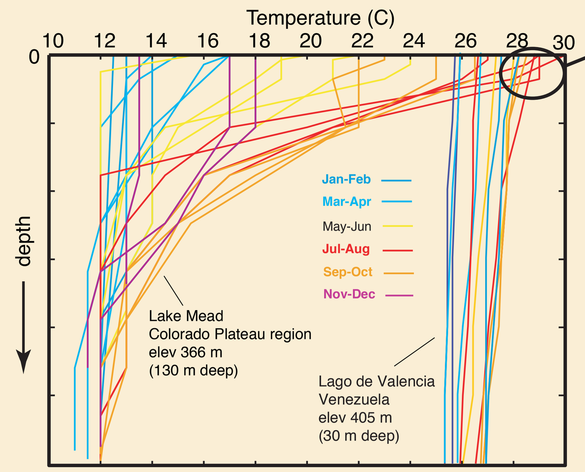
Bidahochi Formation lacustrine micrites also indicate warm growth temperatures consistent with deposition at low elevation - suggesting significant uplift since deposition at ~16 Ma.

Must examine lake carbonate temperature - elevation relationship to interpret the data.

Modern surface water temperatures depend strongly on elevation, but relationship is complicated in temperate climates due to seasonality.



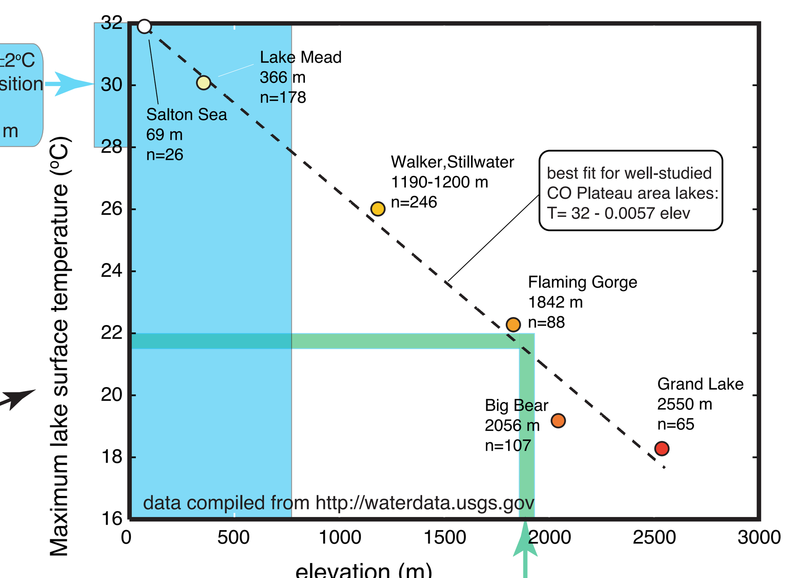
Colorado Plateau region winter, n=31, summer, n=39
Tropical lakes (proxy for hot, humid Mid-Miocene climate) n=243



A l g a e blooms modify pH and provide crystal nucleation sites, triggering carbonate precipitation. As a consequence, most lacustrine micrite should record summer surface water temperatures.

A hot, humid climate modern lake (proxy for Mid-Miocene climatic optimum) will have water temperatures at all depths & all seasons that resemble the surface summer temperature of a temperate lake at the same elevation.

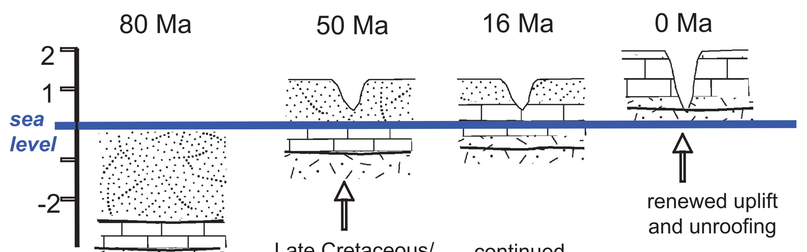
sample T=30±2°C indicates deposition at 16 Ma below 1000 m



TAKE HOME:
Maximum summer lake temperatures recorded by Bidahochi micrites suggest km-scale uplift of the Colorado Plateau since 16 Ma, illustrating how biased temperature signals recorded by carbonates may be exploited to infer robust paleoaltimetry information from complex environmental temperature-elevation relationships.

WORK IN PROGRESS:
- Calibration of method to modern lake carbonates
- Analysis of upper part of Bidahochi section (young as 9 Ma)
- Increase spatial distribution of sampling

Implications for mechanisms of Colorado Plateau uplift



Modified after Flowers et al., in review

(1) Kilometer-scale proto-Grand Canyon incision by 50 Ma indicates considerable relief in Laramide time (Flowers et al., in review)
(2) 30ºC deposition of Bidahochi formation at 16 Ma indicates kilometer-scale uplift since Middle Miocene (this work)

Plateau region gained buoyancy in Laramide time
channel flow (McQuarrie & Chase, 2000), convective removal of lithospheric mantle (England & Houseman, 1988), volatile addition from slab (Humphreys et al., 2003)

Buoyancy for remaining uplift during extension
heating lithosphere from below (Thompson & Zoback, 1979) possible mantle plume (Parsons & McCarthy, 1995), convective removal of the lithospheric mantle (Bird,1979; Humphreys, 1995)